Abstract Topic: FTP

Comparative Study of Chemical Methods for Fuel Removal

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To extend the availability of ITER, tritium stored in the vessel has to be removed on a regular basis. The research on the fuel removal at Forschungszentrum Jülich has been concentrated in recent years on chemical methods including thermo-chemical erosion (TCE) also known as baking in reactive gases, glow-discharge conditioning (GDC) and ion-cyclotron wall conditioning (ICWC). The studies were conducted in the tokamak TEXTOR and in laboratory devices using pre-characterized samples with deuterated carbon layers. GDC, in contrast to TCE and ICWC, is not applicable in the presence of the nominal magnetic field. Our investigations showed that GDC can be operated at a magnetic field of up to 10 mT and is therefore compatible with the ferritic inserts foreseen in ITER. The TCE using oxygen as the removal gas can effectively be employed at elevated temperatures of at least 300°C. Plasma-based GDC and ICWC can also be applied at lower wall temperatures. TCE is equally efficient in cleaning from the wall surface as from the remote areas such as gaps of castellations. GDC is homogeneous along the wall surface except for small recessed areas like gaps. ICWC is typically inhomogeneous along the poloidal circumference. Applying the radial magnetic field, we were able to control the poloidal position of the main IC plasma production. Thus, some wall regions, e.g. the divertor, can selectively be exposed to ICWC. Owing to higher ion fluxes to the wall, ICWC activates a larger amount of neutrals than GDC, which then penetrate in gaps and clean gap walls efficiently. Removal rates with oxygen were typically by a factor of 3 - 10 higher than with hydrogen and ammonia and 10 - 30 than with nitrogen. The estimates using the highest removal rate for ICWC show that about 2 hours are needed to remove the layer deposited within one ITER pulse. The application of ammonia in TCE led to the pealing-off of layers, which is a potential dust production mechanism. However, it appears to be suitable for the non-oxidizing cleaning of metallic mirrors envisaged for optical diagnostics in ITER.

Synopsis Topic: FTP

Comparative Study of Chemical Methods for Fuel Removal

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The reaction fuel for magnetic fusion reactors will contain radioactive tritium. The amount of tritium stored in the vessel of ITER is limited by 700 g for safety reasons. Depending on the materials used for the first wall and the operational regimes this limit can be exceeded in a few hundreds ITER pulses. The co-deposition of tritium with carbon was identified as the main retention mechanism in a carbon-containing device. Yet in a carbon-free device the fuel will be retained, e.g. by the co-deposition with beryllium or in-bulk retention in metals. Regions of material net-deposition, typically found in the divertor as well as in remote areas including gaps of castellated wall structures, are expected to be the main reservoirs for the fuel retention. To extend the availability of ITER, tritium has to be removed from the vessel on a regular basis.

The research on the fuel removal at Forschungszentrum Jülich has been concentrated in recent years on chemical methods including thermo-chemical erosion (TCE) also known as baking in reactive gases, glow-discharge conditioning (GDC) and ion-cyclotron wall conditioning (ICWC). The studies were conducted in the tokamak TEXTOR and in laboratory devices. In particular, electron-cyclotron resonance (ECR) plasma produced in a toroidal device was used as a close proxy for ICWC. Samples with pre-deposited amorphous deuterated carbon layers a-C:D with a D-to-C ratio of ≈0.5 were employed to quantify the removal efficiency. Besides oxygen, which application in ITER is restricted due to the production of tritiated water and the negative impact on the subsequent tokamak operation, alternative gases as hydrogen, nitrogen and ammonia were also evaluated in the experiments. The three methods were characterized by various diagnostic methods, optimized and compared in terms of their removal efficiency. They were also qualified with respect to their homogeneity for different wall regions including remote areas, required removal conditions such as the wall temperature and consequences for the subsequent tokamak operation. Table 1 summarizes the main results and features of these techniques.

Ferritic inserts will be used in ITER to reduce the magnetic field ripple. Our investigations showed, that GDC can be operated at a magnetic field of up to 10 mT and is therefore compatible with the ferritic inserts. However, GDC can only be applied in ITER in maintenance phases with the superconducting coils switched off. On the contrary, TCE and ICWC are applicable in the presence of the nominal magnetic field.

The TCE using oxygen as the removal gas can effectively be employed at elevated temperatures of at least 300°C. TCE in ITER would only be efficient in removing fuel stored in the divertor, which will be kept at 350°C, while the main chamber wall will be at 200°C. GDC and ICWC can also be applied at lower wall temperatures, though their efficiency somewhat increases with rising temperatures. The difference between TCE on one side and GDC and ICWC on the other rests upon the presence of ions for the latter ones. Accelerated

Table 1. Application features and restrictions of chemical fuel removal methods. The required wall temperature is given for oxygen as the removal gas. The removal rates are given for oxygen at a wall temperature of 350°C. The removal rates of TCE are valid for a layer thickness of 200 nm. The rates stated for ICWC were measured applying ECR plasma.

Removal method	Compatibility with nominal B field	Minimum required wall temperature	Homogeneity of removal	D removal rate [at./m^{2}h]	C removal rate [nm/h]
Thermo-chemical erosion (baking)	Yes	300°C	High, also for remote areas	$3{\cdot}10^{21}$	50
Glow-discharge conditioning	No	Room temperature	High for plasma-wetted areas, limited for remote areas	$7{\cdot}10^{21}$	170
Ion-cyclotron wall conditioning	Yes	Room temperature	Limited on a part of plasma-wetted area	$20{\cdot}10^{21}$	600

towards the wall the ions provide the energy necessary to activate chemical reactions at the surface, while in TCE the activation energy is provided by the hot wall.

TCE is equally efficient in cleaning from the wall surface as from the remote areas such as gaps of castellations. GDC is homogeneous along the wall surface. However, it does not reach recessed areas of sizes smaller than the cathode fall thickness, typically several centimeters. Therefore, GDC is less efficient in cleaning side walls of gaps. ICWC is typically inhomogeneous along the poloidal circumference. However, applying the radial magnetic field, we were able to control the poloidal position of the main plasma production in TEXTOR. Thus, some wall regions, e.g. the divertor, can selectively be exposed to ICWC. Owing to higher ion fluxes to the wall of ~10^{19}-10^{20} m^{-2}s^{-1} (cf. ~10^{18} m^{-2}s^{-1} for GDC), ICWC activates a larger amount of neutrals than GDC, which then penetrate in gaps and clean gap walls efficiently.

Throughout the studies oxygen turned out to be the most efficient in removing both deuterium and carbon. Removal rates with hydrogen and ammonia were typically a factor of 3 - 10 and with nitrogen a factor of 10 - 30 lower. The maximum achieved removal rates with oxygen are stated in Table 1. The estimates using the highest removal rate for ECR (the proxy for ICWC) show, that about 2 hours are needed to remove the layer deposited within one ITER pulse. The removal rate of TCE scales linearly with the layer thickness. An a-C:D layer is typically porous, therefore, its entire volume is accessible for the removal gas, making the removal a homogeneous process throughout the layer. The plasma based GDC and ICWC are heterogeneous processes, removing material only from the top surface. Assuming the linear dependence on the layer thickness, the TCE removal rate would equalize ICWC for layers of several μm, which are expected to grow within a few ITER pulses. The application of ammonia in TCE led to the pealing-off of layers, which is a potential dust production mechanism and should be avoided. However, it appears to be suitable for the non-oxidizing cleaning of metallic mirrors envisaged for optical diagnostics in ITER.

After conditioning in oxygen-free gases in TEXTOR, the tokamak operation could easily be re-established. When oxygen was used, an intensive subsequent GDC in hydrogen was necessary to deplete oxygen from the wall prior to tokamak pulses. After the fuel removal experiment, a boronization was used to return to the normal tokamak operation with a low amount of impurities in plasma.